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16. ABSTRACT

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Principles of internal corrosion and corrosion monitoring

Gregory J. Kirmeyer and Gary S. Logsdon

Corrosion is a complex electrochemical phenomenon that cannot always be eliminated but can usually be controlled in a cost-effective manner. Corrosion may be uniform and attack a surface evenly or may cause severe localized problems, such as a crevice or pit. For the corrosion reaction to proceed, all components of an electrochemical cell—an anode, a cathode, a connection between the anode and cathode, and a conducting solution—are required. Methods for documenting corrosion range from simple visual inspections to complex scale analyses. Laboratory and pilot tests can be used to define the extent and magnitude of corrosion. Corrosion control programs should be developed with a two-phased approach in mind: changing water chemistry and using corrosion-resistant materials. Monitoring is important to ensure that the corrosion control program continues to meet its desired objective.

With the passage of the Safe Drinking Water Act (SDWA) in 1974, the United States government, through the US Environmental Protection Agency (USEPA), began to deal with providing safe drinking water for public use. Although, for the most part, water purveyors have provided safe, potable drinking water to consumers for many decades, this new act required the establishment of first interim and then revised primary drinking water standards—maximum contaminant levels (MCLs)—that were recommended to protect public health.

In response to the SDWA, the USEPA established the National Interim Primary Drinking Water Regulations (NIPDWR) in 1977 to set MCLs for certain inorganic chemicals, including lead and cadmium. These regulations required that the MCLs be met at a consumer's tap, whereas previous regulations had been concerned only with water quality in a utility's distribution system. Later, the USEPA established the National Secondary Drinking Water Regulations that suggested guidelines for iron, copper, and zinc. Finally, in recognition of the potential contamination of water as it travels through a distribution system and premise plumbing, the USEPA amended the NIPDWR to include corrosivity.[1] These amendments require a utility to determine the corrosive characteristics of its water and to determine the materials of construction in the distribution system including service lines and home plumbing systems. Based on this monitoring program, an initial determination as to corrosion in a water system is to be made.

Problems caused by corrosion

A water that exhibits corrosiveness can cause problems in distribution pipelines and home plumbing systems. These problems can be grouped into three categories: health, aesthetic, and economic.

Health. Corrosion of materials in plumbing and distribution systems increases the concentrations of metal compounds in the water. Lead, cadmium, and other heavy metals are present in various amounts in pipe material, and there is concern for the possible health hazards created by corrosion and subsequent leaching and ingestion of these materials.

Aesthetics. Secondary contaminants—copper, iron, and zinc—are also leached from plumbing and distribution systems. These contaminants, when present in concentrations above the suggested limits, can render the water aesthetically undesirable for consumption because of taste, color, or staining characteristics.

Economics. Deterioration of plumbing and distribution systems because of corrosion frequently results in extensive and costly replacement. Corrosion of copper pipe is usually characterized by a uniform etching or thinning of the pipe wall. Failure occurs only when corrosion has damaged the structural integrity of the pipe so much that leakage becomes a problem. Corrosion of galvanized steel is normally characterized by pits that develop in the pipe surface. These pits may eventually penetrate the pipe wall and cause leakage. As the pipe deteriorates, tubercles build up over the developing pits. These tubercles tend to form a blockage in the pipe and can eventually restrict the water flow so much that the pipe must be replaced. Internal corrosion of unlined, cast-iron mains can cause higher pumping costs for a utility.

Principles of corrosion

Defining corrosion is in order before discussing the principles of corrosion. The word *corrosion* is derived from the Latin word *rodere* ("to gnaw"). Corrosion may be thought of as the gnawing away or attack on a material, usually by some chemical or electrochemical means. Corrosion has also been defined as "nature's way of taking from man what man has taken from nature."[2]

This process of taking from nature involves extracting ores from the earth and converting them into usable metals. During the manufacturing process, which usually requires large amounts of energy in the form of heat, oxygen and moisture are removed. The finished metal is highly stressed and contains a quantity of stored energy.

Letting a finished metal product come into contact with oxygen and moisture by burying it in the ground or exposing it to the atmosphere may trigger release of the stored energy in the product and allow corrosion to occur. The metal may eventually return to its original state—an ore.

The speed at which a metal corrodes depends on the amount of energy required in the manufacturing process. Metals produced with large amounts of energy usually corrode quickly, whereas metals that are generally used in their original state are resistant to corrosion.

Common forms of internal corrosion

Internal corrosion occurs in several, widely differing forms, which are usually classified according to the appearance of the corroded metal, and can be either uniform or localized.[3]

Uniform corrosion. Uniform corrosion occurs when the metal corrodes at approximately the same rate over its entire surface. Uniform attack usually results in an even thinning of the pipe wall, until the pipe can no longer hold up under the

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water pressure or external loads and structural failure occurs.

Localized corrosion. Localized corrosion occurs when the metal surface is attacked unevenly so that some areas are severely affected by corrosion while adjacent areas may not be affected. Localized corrosion may be subdivided into several categories: galvanic, pitting, crevice, and erosion.

Galvanic corrosion. Galvanic corrosion may occur when two dissimilar metal pipes are placed in direct or electrical contact. The difference in electrical potential that then exists between the two metals produces electron flow between them. Corrosion of the more corrodible metal is usually increased whereas attack of the more resistant material is decreased, compared with the behavior of the metals when they are not in contact.

Galvanic corrosion can often be recognized by the increased corrosion close to the junction of two dissimilar metal pipes. Therefore, when copper and iron pipe are joined together, corrosion can be avoided by using dielectric insulators to separate the pipes.

Crevice corrosion. Crevice corrosion is intense localized corrosion that occurs within crevices and other shielded areas on pipe surfaces. It is usually associated with small volumes of stagnant solution trapped by holes, gasket surfaces, pipe joints, surface deposits, and corrosion products. With time, the condition of the water in such crevices can become quite different from that of the free-flowing water. Crevice corrosion is usually attributed to one or more of the following changes that can occur in a crevice: change in pH, change in the oxygen concentration, buildup of an aggressive ion, or depletion of a chemical corrosion inhibitor.

Pitting corrosion. Pitting is a form of localized attack that can eventually result in holes in the metal pipe. Pits can be of various shapes and sizes, and the degree of attack can range from mild to severe. The indentation that results from pitting is responsible for the pit's continued growth, for the same reasons mentioned in the discussion of crevice corrosion. A pit can be considered a self-formed crevice. Pitting usually requires an extended initiation period, which depends on the type of pipe and water quality, before visible pits appear. The rapid penetration of the pipe wall and the development of pinhole leaks make pitting one of the most destructive forms of corrosion.

Erosion. When the high velocity of water moving through a pipe increases the rate of attack because of mechanical wear, the attack is called erosion. This type of corrosion is accelerated by localized removal of a protective film, and the metal is removed from the pipe surface both as dissolved ions and solid corrosion products. Erosion is characterized by smooth-bottomed, shallow pits that usually exhibit a directional pattern and thrives on turbulent, high-velocity conditions. Erosion is frequently found in bends and elbows of piping systems.

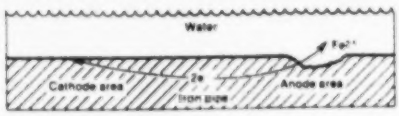

Figure 1. Corrosion cell for iron pipe contacting water

TABLE 1
Factors affecting the corrosivity of drinking water[4]

Factor	Effect on Corrosivity
pH	Low pHs generally accelerate corrosion.
Dissolved oxygen	Dissolved oxygen in water induces active corrosion, particularly of ferrous materials.
Free chlorine residual	The presence of free chlorine in water promotes corrosion of ferrous metals and copper.
Low buffering capacity	Insufficient alkalinity to provide buffering capacity to the water and provide protective films.
High halogen and sulfate-alkalinity ratio	A molar ratio of strong mineral acids much above 0.5 results in conditions favorable to pitting corrosion.
Carbon dioxide	Carbon dioxide is particularly corrosive to copper piping.
Total dissolved solids	Higher concentrations of dissolved salts increase conductivity and may increase corrosiveness. Conductivity measurements may be used to estimate total dissolved solids.
Calcium	Calcium generally reduces corrosion by forming protective films with dissolved carbonate.
Silica	Silica forms protective films over metal surfaces.
Tannins	Tannins form protective organic films over metals.
Flow rates	Turbulence at high flow rates allows oxygen or carbon dioxide to reach the surface more easily, removes protective films, and causes higher corrosion rates.
Metal ions	Certain ions, such as copper, can aggravate corrosion of downstream materials. For example, copper ions can increase the corrosion of galvanized pipe.
Temperature	High temperature increases corrosion reaction rates. High temperature also lowers the solubility of calcium carbonate and calcium sulfate and thus may cause scale formation in hot-water heaters and pipes.

The basic corrosion reaction

Electrochemical corrosion can be viewed in terms of oxidation and reduction reactions. For corrosion to occur, all the components of an electrochemical cell are required (Figure 1). At the anode, the oxidation of a metal occurs:

$$\text{Metal} \rightarrow \text{Metal}^{n+} + ne^-$$

At the anode, two reactions are possible for corrosion of iron pipe:

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + 2H^+ + 2e^-$$
$$Fe + HCO_3^- \rightarrow FeCO_3 + H^+ + 2e^-$$

The former reaction occurs when the carbonate concentration is low, whereas the latter occurs when the carbonate concentration is high. At the anode, corrosion can be inhibited when the oxidation products form a stable solid, such as an oxide, hydroxide, or carbonate, that adheres to the pipe surface and prevents or slows direct contact between the metal and the corrosive water, thus providing a barrier to corrosion reactions. This inhibition of corrosion is known as passivation. The compounds that form when iron corrodes depend on several factors, including pH and buffer capacity. Siderite ($FeCO_3$) may form and slow the corrosion rate. If conditions favor the formation of iron hydroxides, such as $Fe(OH)_2$ and $Fe(OH)_3$, soft and porous coatings may not inhibit corrosion.

Electrons are transferred to the cathode when corrosion occurs, and several reduction reactions may occur as follows:

(1) for acid solutions,

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

(2) for basic solutions,

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

(3) for reduction of chlorine,

$$HOCl + H^+ + 2e^- \rightarrow Cl^- + H_2O$$

(4) for hydrogen evolution,

$$2H^+ + 2e^- \rightarrow H_2$$

Thus, the factors favoring corrosion include a low pH and a high concentration of oxidizing substances, such as dissolved oxygen and free residual chlorine. Movement of hydrogen gas away from the cathode area promotes continued corrosion. Factors that affect the corrosivity of drinking water are listed in Table 1.

Corrosion of iron pipe[3]

Corrosion of iron pipe is characterized by pitting and the formation of iron oxide tubercles. In general, life spans for unlined iron pipe in water with low pH and

alkalinity are quite short. Failure can usually be attributed to plugging and pinhole leaks. The pitting and tuberculation process is initiated when, for any reason, the rate of iron dissolution is momentarily increased at particular points on the pipe surface. This initiation process usually occurs in a surface scratch, near surface irregularities, in standing water, and near iron oxide deposits. Once initiated, pitting occurs by an autocatalytic process.

Within the pit, rapid dissolution of iron occurs, and oxygen is depleted. Because iron dissolution continues, an excess positive charge develops. This positive charge is balanced by the migration of chloride and other ions into the pit to maintain electroneutrality. Thus, the pit contains a high concentration of $FeCl_2$, and as a result of hydrolysis,

$$FeCl_2 + 2H_2O \rightarrow Fe(OH)_2\,(s) + 2H^+ + 2Cl^-$$

a high concentration of hydrogen ions exists. Both hydrogen and chloride stimulate the dissolution of iron, and the entire process accelerates with time.

At the interface between the pit and the adjacent surface, iron hydroxide tubercles form because of the interaction between the hydroxide produced by the cathodic reaction and the dissolved iron:

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2\,(s)$$

Dissolved oxygen can further oxidize the iron (II) hydroxide to other oxides. The different colored layers in a tubercle are evidence of this oxidation by dissolved oxygen. Favorable conditions can result in formation of $FeCO_3$ and subsequent iron compounds, which form a protective layer on iron pipe and inhibit corrosion. A discussion of the mechanism of corrosion inhibition by formation of $FeCO_3$ has been presented previously.[5]

Corrosion of galvanized pipe

Deterioration of galvanized pipe occurs in two stages. Initially, only the galvanized or zinc layer corrodes until iron is exposed. Corrosion of the galvanized layer depends on pH, carbonate concentration, and flow.

Once the galvanized layer is penetrated and iron is exposed, the galvanized pipe begins to perform as an iron pipe. Initially, the zinc sacrificially corrodes, offering protection to the iron. Eventually, the iron base metal of the pipe begins to pit, and iron oxide tubercles are formed.

Corrosion of copper pipe[3]

The corrosion of copper pipe is generally uniform. In the presence of dissolved oxygen, a thin film of cuprous oxide is formed over most of the metal's surface. This film promotes a constant corrosion rate that is normally only a fraction of the corrosion rate of iron or galvanized pipe. However, pitting of copper pipe can occur. Pitting is usually caused by a breakdown of the passivation film. The film can be disturbed by high-velocity water flow or dissolved by either carbonic acid or organic acids that are found in some freshwaters. Chlorides also tend to promote pitting by increasing the porosity of the passivation film. Chlorine increases the oxidation of copper and prevents the establishment or continuation of the protective film of cuprous oxide.

Near a soldered joint, a galvanic couple is formed between the copper pipe and the solder. The copper acts as the cathode, and the solder acts as the sacrificial anode. In the case of 50-50 lead-tin solder, the principal anodic reaction is the dissolution of lead and the subsequent leaching of lead into the drinking water. The problem with leaching of lead is eliminated with the use of 95-5 tin-antimony solder, which corrodes to form a passivation film that inhibits metal leaching from the solder.

Corrosion of lead pipe[3]

Lead pipe has been in service for many years in many older water distribution systems. Although lead pipe is durable for use with potable water, the toxicity of trace amounts of dissolved lead should preclude its use in soft potable water.

The corrosion of lead pipe depends very much on pH and alkalinity. At very low alkalinities, lead is soluble throughout the pH range of drinking water. In water containing carbonate alkalinity, an insoluble film of basic lead carbonate forms in the intermediate pH region. For example, at a total alkalinity of 20 mg/L and a pH of 9.5, the concentration of lead in water circulating through lead pipe was less than 50 µg/L in an USEPA experiment.[6] The film of basic lead carbonate performs two functions: (1) by adhering to the metal surface, the film forms a physical barrier between the metal and the water, and (2) the basic carbonate or carbonate solid phase limits the lead solubility and, therefore, reduces the amount of lead that can be leached into the drinking water. However, even in systems containing high pH values, corrosion can occur at very low and high alkalinities.

Corrosion in the treatment plant[7]

The potentials for deterioration within the treatment plant are present from the raw water intake and lift station to the treated-water storage tank. Because of repeated wetting and drying, intake screens and trash racks are subject to corrosion. Unusual flow patterns through meters can erode pipe surfaces. Also, the sharp metal edges of inlet weirs are known to be areas of high stress. These highly stressed areas are more likely to corrode than less highly stressed areas.

Because the optimum pH for flocculation is often at a corrosive level, metal in flocculation basins must be protected. Sedimentation basins are also subject to corrosion. Sludge deposits, which can set up localized corrosion cells, and the abrasiveness of sludge are other sources of corrosion. Chemicals used in water treatment plants can present special problems. For example, inorganic and organic coagulants are corrosive. Also, the commonly used disinfectants chlorine and ozone are highly corrosive.

Standard treatment can make potable water more aggressive to the materials commonly used in home plumbing and distribution systems. Use of alum decreases pH and increases sulfate concentrations. Use of gaseous chlorine and hydrofluosilicic acid also reduces pH and alkalinity and adds chloride and fluoride to the water. There have even been instances where bringing a filter plant online caused significant corrosion-related problems for customers because alum coagulation reduced pH and alkalinity.

Methods of monitoring corrosion[8]

Utilities are responsible for the integrity of the distribution system and the quality of the water delivered to customers. A program should be undertaken to monitor the condition of the distribution system and the quality of tap water. Causes and effects of corrosion can be measured in various ways, ranging from simple visual observation of main taps to complex analysis using the scanning electron microscope. These methods can generally be divided into two broad categories for the purpose of discussion: (1) the water quality characteristics, and (2) the pipe material. Both an aggressive water and a susceptible piping material are necessary for corrosion to occur.

Water quality. *Indexes.* Water utilities have been required for several years to analyze their waters for corrosive characteristics, including pH, alkalinity, hardness, calcium, and total dissolved solids (TDS). These characteristics can be used to calculate corrosion indexes and to compare a particular water's corrosiveness with that of similar waters. Common indexes include the Langelier Index (LI), the Ryznar Index (RI), the Aggressive Index (AI), and the Driving Force Index (DFI).[9] All of these indexes are based on the solubility of calcium carbonate. The corrosion indexes may be applied in corrosion control for certain types of waters but may not be applicable for the very soft waters of the northwestern and northeastern United States. Riddick developed an empirical corrosion index, which included carbon dioxide, hardness, alkalinity, chlorides, nitrates, dissolved oxygen, and silica.

Water quality changes in distribution and home plumbing systems.[4] A survey of water quality as the water enters the transmission lines from the source of supply must be completed and compared with analyses of samples collected at various locations within the distribution

TABLE 2

Water characteristics of interest for various water main materials

Water Main Material	Water Characteristics of Interest
Ductile and cast iron	Color, conductivity, dissolved oxygen, iron, manganese, pH (and alkalinity and calcium, if main is cement-lined)
Steel	Color, conductivity, dissolved oxygen, iron, manganese, pH
Concrete cylinder	Alkalinity, calcium, conductivity, pH
Asbestos-cement	Asbestos fibers, iron silica
Galvanized steel	Alkalinity, cadmium, color, conductivity, dissolved oxygen, iron, lead, pH, zinc

TABLE 3

Metals surveyed in different studies of tap water quality[10]

Location	Surveyor	Metal																
		Pb	Cd	Cu	Zn	Fe	Mn	Ni	Cr	Sn	Sb	Co	Ag	Hg	Al	Ca	Mg	Na	K
Seattle, Wash.	USEPA	X	X	X	X	X	X									X	X		
Seattle, Wash.	Seattle Water Metals Survey	X	X	X	X	X	X	X	X	X	X	X	X						
Seattle, Wash.	National Heart and Lung Institute	X	X	X	X														
Boston, Mass.	USEPA	X	X	X	X	X	X	X	X			X	X			X	X		
Oslo, Norway	NIPH	X	X	X	X	X	X	X	X			X		X	X	X	X	X	X
Community Water Supply Survey	USPHS	X	X	X	X	X	X	X	X			X	X						

system to determine whether corrosion is affecting the water quality in the transmission and distribution system. This survey should include variables such as different sources of supply, different pressure zones, secondary treatments within the distribution system, open reservoirs, and different types of pipelines. Choice of the appropriate constituents for analyses should be based on the composition of the material being used. For example, if the transmission lines are concrete or asbestos-cement and storage reservoirs are concrete, then pH, alkalinity, and calcium (or hardness) are the logical constituents for analyses. Analyzing for substances that may protect pipe, such as iron, manganese, and silica, would also be appropriate. Table 2 lists constituents that are suggested for water quality analysis for different types of pipe material and includes substances that may increase corrosion, decrease corrosion, or be products of corrosion. These constituents are not all of the components needing analysis under conditions of potential corrosion but indicate the rationale to be followed in selecting constituents for analysis. Changes in the values for these constituents indicate corrosion of the material is occurring.

No easy method exists for determining the quality of water at the customer's tap except to sample there. Differences in the values of constituents for standing and running water samples collected at the same location will normally indicate whether corrosion is occurring in the home plumbing system or in a service line. A sample of standing water is water that has remained for an extended period of time, e.g., overnight, in a plumbing system. This sample is the first flush of water from the plumbing system. Samples of running water are those collected from the customer's tap after any standing water has been flushed from the system. Running water is generally the fresh, flowing water from the utility main. Many different constituents have been included in previous analyses of tap water. In surveys of metals in tap water in Seattle, Wash., Boston, Mass., and Oslo, Norway, between four and twenty constituents were monitored. Table 3 indicates the diversity of metals monitored or screened in five separate surveys.[10]

As with the sampling program for the distribution and transmission system, the sampling program at the consumer's tap must address the various plumbing materials used. Because most plumbing systems are a mix of several different types of pipe, results of analyses may be difficult to interpret. Therefore, each tap sample should be analyzed for a standard series of constituents. If standard types of pipe—galvanized, black steel, copper, or lead—are in use, the minimum set of constituents should include cadmium, lead, copper, zinc, and iron. Other constituents include manganese, tin, aluminum, chromium, nickel, antimony, pH, alkalinity, and specific conductance.

Complaints and questionnaires. Records of complaints about water quality should be kept in an orderly manner and should include the following information: customer's name, location, date, nature of complaint, and remedial action taken. These records provide a good history of when changes made in the system, such as a new water source or a treatment change, have caused an increase or decrease in corrosion. Although these records are good indicators of the changes in corrosiveness of water, they do not necessarily document the extent of the problem. Sending a questionnaire to a random sample of customers is useful in determining the extent of corrosion.

Extent of staining. Testing for staining can be useful as a visual measure of corrosion, especially for comparing treatment methods. The water exiting treatment pipe loops can be discharged onto a white, porcelain plate, and the staining effects of different treatments compared. This is an inexpensive method and can be useful in presenting results of a pilot program to utility management.

Pipe and coupon testing program

Following the sampling program to determine water quality, development of a program to gather pipe specimens for evaluation is suggested. Normally, gathering the pipe section or pipe taps is a relatively simple task, but the evaluation is much more difficult. This section will discuss methodology that has been successfully used in the past for measuring corrosion and for developing pipe sampling and pilot testing programs.

Methods of analysis. Water utilities, the American Society of Testing and Materials (ASTM), and the National Association of Corrosion Engineers have developed standard procedures for testing pipe coupons including visual observation, micrographs, weight loss, pitting potential, scale analysis, and corrosion probes.

Visual inspection. Visual inspection of the pipe can be used to classify both the extent of tuberculation and sometimes the type of corrosion. For example, a galvanized pipe may be plugged by tubercles with most of the interior area closed off by rust, or a copper pipe may be etched with uniform corrosion. Books with illustrations of different types of corrosion are available to help classify corrosion.

Micrographs. Electron microscopes have been used to view the interior portions of pipes. For example, asbestos-cement pipe may have asbestos fibers protruding from the surface as the cement bonding material is dissolved by an aggressive water. Micrographs could possibly be used to compare the surface texture of new and old pipes.

Weight loss. Because internal corrosion dissolves the metal pipe material, the weight of the pipe will decrease with time, and this decrease can be measured. Tedious cleaning and weighing procedures must be followed, but this is one of the best procedures used for test comparisons of various water treatment processes and pipe materials.

Pitting potential. Pitting corrosion (corrosion in which pit depths are greater than or equal to 25 percent of pit widths) may cause pipe failure through penetra-

TABLE 4
Schedule of repairs

Repairs	Year	Cost dollars
Replace service line	1982	300
Interim repair	1987	75
Leak repair	1989	100
Leak damage	1989	150
Replace accessible plumbing	1992	1000

TABLE 5
Present worth values without corrosion treatment

Item	Year	Cost dollars	PWF*	Present Worth dollars
Replace service line	1982	300	1.00	300
Interim repair	1987	75	0.62	46
Leak repair	1989	100	0.51	51
Leak damage	1989	150	0.51	78
Replacement	1992	1000	0.38	385
Total				860

*Present worth factor for 10 percent (rounded off)

tion of pipe walls. The pit depths of test specimens and pipe sections can be measured with a micrometer in many cases. The use of a microscope with a graduated, fine-focus adjustment is even more versatile in measurements of pit depth and width. Calculations of pitting rates are valuable in predicting service life for various materials and water conditions.

Scale analysis. Analysis of the coating or scale found on a pipe wall is important because it may indicate why the pipe is protected or is deteriorating. For example, a high concentration of calcium or silica on the pipe wall could act as a barrier to the diffusion of oxygen and thereby reduce the corrosion rate. Scale analysis can also be used to determine the effectiveness of a treatment method designed to lay down a specific coating. Methods for the analysis may include X-ray fluorescence, X-ray diffraction, atomic absorption, emission spectroscopy, infrared spectroscopy, and gravimetric methods.

Corrosion probes. Probes designed to measure the corrosion rate of various metals are available. Usefulness of these probes depends on the water characteristics. They are best used to follow short-term changes in the corrosion rates of various water supplies and corrosion treatment without having to remove the test unit from the source. As with weight loss determinations, probe readings do not necessarily indicate what is happening in the field unless they are verified by actual comparison with an existing pipe that has been in place for quite some time.

Field sampling program. *Transmission and distribution systems.* Several methods are available for sampling and evaluating the condition of a transmission and distribution system. If transmission lines are large, a walk-through inspection of certain sections would be worthwhile. Distribution reservoirs and tanks can also be investigated in this manner. For the distribution system, pipe taps and pipe sections that are being removed or repaired provide an excellent record of the condition of the system if the specimens are properly and accurately tagged and preserved. The information recorded for each specimen should include who removed the pipe, where, why, its condition upon removal, age, and other pertinent remarks. Meters and valves can also be inspected as part of the routine maintenance program. Using methods such as visual inspection, weight loss, pitting depth and rate, scale analysis, head loss readings, and records of leaks, one can document the extent of corrosion and quantify its magnitude.

Plumbing systems. Most utility personnel are more knowledgeable about the methods of evaluating corrosion in a distribution system than in home plumbing systems. Since the NIPDWR became effective, degradation of water quality owing to plumbing corrosion has indirectly become a purveyor's problem to solve. Contrary to the practice of most utilities that have selected corrosion-resistant materials for many years for use in their distribution systems, many builders, plumbers, contractors, and homeowners have not chosen corrosion-resistant materials to put in home and building plumbing systems. In many cases, unlined metallic pipes are quite susceptible to corrosion, especially in the environment of soft, corrosive surface waters.

A program in which various types of pipe of different ages are removed from homes and evaluated is the best way to determine the condition of a home's piping. Evaluation methods include visual inspection, determining pitting potential, and scale analysis. Questioning the homeowner about possible problems with low pressure can indicate the corrosive action of water on certain types of piping. Plumbing repair shops probably know the condition of home plumbing systems and will usually share their knowledge with a utility. Most shops stockpile old pipe, hot-water tanks, and other equipment before disposing of them. A visit to several plumbing shops will provide a quick look at the problem areas. Based on this investigation, the typical service life of the various types of plumbing can be estimated, and a cost can be placed on the deterioration of home plumbing systems caused by corrosive water.

Pilot plant program. Several methods are available for testing pipe coupons and evaluating the effectiveness of alternative treatment programs. Most of these methods involve exposing a piece of metal (or pipe section) to the water and then measuring the corrosion rate by weight loss or some other method after a given length of time. Metals initially corrode at very high rates, but corrosion usually slows down with time. Rates for some metals, such as copper, may stabilize within two or three months, whereas corrosion of galvanized pipe may not approach steady-state conditions for more than a year. At least two methods of evaluation have been used with some degree of success—immersion and flow-through tests. The immersion test involves suspending metal coupons in water for various times (one to six months) to measure the resulting corrosion rates. Some investigators perform batch tests, others use a continuous flow of water through the container, and some combine the two variations by simply changing the water periodically during the test period. The flow-through tests, as used by the Illinois State Water Survey and based on an ASTM standard (D2688-IDC), involve maintaining a continuous flow through lengths of actual pipe. New pipe sections are inserted into a pipe loop in such a manner that they can be removed at preset time intervals for evaluation. This seems to be a more reliable test method than immersion testing, although it is much more tedious and time-consuming. The suggested testing period is six to twelve months or more.

Comparison of field and pilot tests. In many cases, the results from field specimens do not correlate well with results from laboratory or pilot-plant tests. Thus, a comparison must be made before conclusions are drawn. Even if corrosion rates in the field do not correlate well with pilot tests, the pilot tests are still valuable for comparing various alternatives for chemical treatment. Pilot tests can also be used to estimate service life of actual plumbing pipe under different chemical treatments. Service life can be estimated by using relative corrosion rates or a percent reduction in the corrosion rate based on pilot tests and then applying the percent reduction to the pipe in the field. Carrying the analysis one step further, the relative corrosion rates from pilot-plant tests can be used to estimate the costs or benefits associated with corrosion because of a new water source or a change in chemical treatment. Having this type of knowledge

TABLE 6
Present worth values with corrosion treatment

Item	Year	Cost dollars	PWF*	Present Worth dollars
Replace service line	1982	300	1.00	300
Interim repair	1989	75	0.45	34
Leak repair	1994	100	0.33	33
Damage repair	1994	150	0.33	49
Replacement	1999	1000	0.20	200
Total				616

*Present worth factor for 10 percent (rounded off)

before a change in water quality is made is invaluable.

Costs of corrosion

The significance of corrosion costs to the overall economy of the United States has been reported by the National Bureau of Standards (NBS). Corrosion costs in the United States were estimated at $70 billion annually in 1975. The direct-cost portion of this amount is approximately 25 percent, which in proportion to the gross national product is 4.2 percent.[11] The proportion of costs that can be avoided by corrosion control measures is approximately 15 percent of the direct-cost portion. The same NBS report indicated that the annual costs in the water supply field total approximately $700 million. These costs are only for distribution systems. Often, however, a far greater portion of corrosion costs are incurred through damage to interior piping and plumbing systems. Replacing a water heater could cost the homeowner $200-$300. The cost of replacing accessible plumbing in a home would be several hundred dollars. If all of the plumbing in a home has to be replaced, costs could easily reach $2000 to $3000.

Corrosion damage can be quantified in monetary terms, and benefits of corrosion reductions can also be calculated. The approach to such calculations is based on knowing the service life of pipe under existing conditions and then projecting service life as the water quality changes. By performing a present-worth analysis and comparing monetary benefits of longer service life versus the costs of water treatment, one can calculate a cost-benefit ratio. A brief example of calculating a cost-benefit ratio follows.

If, under existing conditions, pipe in a single-family dwelling has a 30-year service life and the house is 20 years old, then the pipe has 10 years of useful life until it becomes so plugged with rust that neither flow nor pressure can be maintained at adequate levels. Interim repairs, leak damage, and total replacement are assumed to occur as shown in Table 4. If a treatment method is instituted to reduce corrosion by 40 percent, the repairs, pipe damage, leaks, and replacement will be put off to some point in the future. Tables 5 and 6 list present-worth values of the corrosion damage without and with treatment, respectively. These calculations indicate that the cost saving attributable to a 40-percent reduction in the corrosion rate will be $244 ($860 - $616) over the life of the plumbing. If treatment costs $0.05/3700 L (1000 gal), which is very conservative on the high side, then the present worth of these costs is $57.90. Thus, the benefit-cost ratio becomes $244:$57.90 or 4.2:1. For every dollar spent the return is $4.20. This is considered a very beneficial ratio.

The cost aspect of corrosion is a powerful tool to be used by a utility in presenting persuasive arguments for reducing corrosion damage. Managers and customers understand dollars and cents, and this method of presenting data should be given serious consideration.

Summary and conclusions

Federal regulations that require monitoring of water quality and surveying of materials in the distribution system are good starting points. Corrosion is a complex phenomenon that can seldom be totally eliminated. Normally, a utility can hope to reduce the problem to a more tolerable level by a two-phased approach: changing the water chemistry and selecting the most corrosion-resistant materials for a particular water.[12]

Changing the water chemistry should be based on laboratory and pilot tests. Benefits in terms of water quality and reduced corrosion should be documented. Several methods are available for changing the water quality, including using chemical inhibitors and blending a more mineralized groundwater with soft, surface supplies. Chemical inhibitors can be effective, but their use is often opposed by a utility's customers. In addition, inhibitors can be quite expensive. Chemical inhibitors can be used effectively at the point of use, especially on hot-water systems. Blending of water supplies is a good solution, if the less corrosive water is available in the appropriate quantity and quality to effect the desired change in water quality. Most utilities have not blended water for the purpose of controlling corrosion but have traditionally used the cheapest method of supply.

Coupled with the changes in water quality, a program that selects corrosion-resistant materials is usually the best long-term solution. Measures that have been used by some utilities include cleaning pipelines and lining them with cement; using stainless steel, brass, bronze, or plastic materials; using plastic piping for service connections; changing plumbing codes to allow plastic piping in homes; using glass-lined water heaters; and requiring the use of low-lead solders.

The methods just described are general and must be tailored to the specific water quality and distribution system. Once a plan is implemented, a monitoring program should make certain the corrosion control program works effectively.

References

1. Corrosivity. *Federal Register*. 45:168:57332 (Aug. 17, 1980).
2. LYCO, C. Introducing Corrosion. British Columbia Water and Waste Assn., Corrosion Control Seminar Proc., Richmond, B.C. (Dec. 1980).
3. HERRERA, C.E. & KIRMEYER, G.J. Fundamentals of Internal Corrosion. British Columbia Water and Waste Assn., Corrosion Control Seminar Proc., Richmond, B.C. (Dec. 1980).
4. Manual for Determining Internal Corrosion Potential in Water Systems. Water Quality Committee, Pacific Northwest Section, AWWA (Oct. 1980).
5. SONTHEIMER, H.; KÖLLE, W.; & SNOEYINK, V.L. The Siderite Model of the Formation of Corrosion-Resistant Scales. *Jour. AWWA*. 73:11:572 (Nov. 1981).
6. SCHOCK, M.R. & GARDELS, M.C. Plumbosolvency Reduction by High pH and Low Carbonate—Solubility Relationships. *Jour. AWWA*. 75:2:87 (Feb. 1983).
7. O'BRIEN, B. & STORE, A.W. Corrosion Protection in Water Treatment Plants. British Columbia Water and Waste Assn., Corrosion Control Seminar Proc., Richmond, B.C. (Dec. 1980).
8. KIRMEYER, G.J. Internal Corrosion of Water Piping Systems. Water Supply Short Course, Univ. Washington, Seattle, Wash. (Sept. 1981).
9. SINGLEY, E.J. The Search for a Corrosion Index. *Jour. AWWA*. 73:11:579 (Nov. 1981).
10. HOYT, B.P.; KIRMEYER, G.J.; & COURCHENE, J.E. Evaluating Home Plumbing Corrosion Problems. *Jour. AWWA*. 71:12:720 (Dec. 1979).
11. RYDER, R.A. The Costs of Internal Corrosion in Water Systems. *Jour. AWWA*. 72:5:287 (May 1980).
12. KIRMEYER, G.J. ET AL. Seattle's Corrosion Control Plan, Chemical Treatment Coupled With Selection of Corrosion Resistant Materials. British Columbia Water and Waste Assn., Corrosion Control Seminar Proc., Richmond, B.C. (Dec. 1980).

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